STEEL SHEET WITH EXCELLENT BENDABILITY

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates to a high-strength steel sheet with excellent bendability, especially tight bendability (ultimate deformability). More particularly, the present invention relates to a high-strength steel sheet which exhibits excellent bendability despite its high or ultra-high strength ranging from 600 to 1400 MPa.

2. Description of the Related Art

Steel sheets used for press working in automobile and machine industries are required to have both good strength and good ductility, and such requirements are becoming more rigorous than before.

There is known a steel sheet in which strength and ductility stand together. It is a steel sheet of ferrite-martensite dual phase (DP) in which the ferrite matrix contains the microstructure composed mainly of martensite which has transformed at low temperatures (disclosed in, for example, Japanese Patent Laid-open No. 122820/1980). This steel sheet is excellent in ductility as well as shape freezing properties in press working. The latter is attributable to a large number of free dislocations which appear in the region where martensite forms, and such dislocations eliminate yield elongation, thereby reducing yield stress. With a properly controlled microstructure, the steel sheet will have both high tensile strength (TS)

and high elongation (El).

There is also known a retained austenite steel sheet (or TRIP steel sheet) with improved ductility. It contains retained austenite in the structure so that it undergoes transformation induced plastic deformation during working. For example, Japanese Patent Laid-open No. 43425/1985 discloses a dual-phase steel sheet with high strength as well as excellent ductility. This steel sheet is composed of no less than 10 vol% of ferrite and no less than 10 vol% of retained austenite, with the remainder being bainite or martensite or a mixture thereof. According to the disclosure, retained austenite produces the effect of working-induced transformation and soft ferrite produces the effect of high ductility. With the structure as specified above, ferrite and retained austenite contribute to ductility and bainite or martensite contributes to strength.

All the steel sheets mentioned above are characterized by excellent elongation properties (especially uniform elongation). In particular, TRIP steel sheets benefit from very high elongation and very good formability (for stretching and deep drawing) owing to retained austenite therein. However, it is known that they are generally inferior to solid-solution strengthened steels in local deformation properties (bendability and bore-expandability) and ultimate deformation properties (tight bendability). Although good bending properties (particularly good tight bendability) are essential for steel sheets for press forming in the automobile industry, there have been no steel

sheets developed so far which meet these requirements.

SUMMARY OF THE INVENTION

The present invention was completed in view of the foregoing. It is an object of the present invention to provide a high-strength steel sheet with excellent bendability, especially tight bendability, despite its high or ultra-high strength ranging from 600 to 1400 MPa.

The present invention is directed to a steel sheet with excellent bendability comprises C (0.06 mass% to less than 0.25 mass%), at least one of Si and Al (total 0.5-3 mass%), Mn (0.5-3 mass%), P (no more than 0.15 mass%, excluding 0 mass%), and S (no more than 0.02 mass%, excluding 0 mass%), wherein the main structure of the steel sheet comprises retained austenite (5-30 area%) and ferrite (no less than 50 area%) and there exist no more than 40 carbide grains per 2000 μm^2 in the steel sheet.

In addition, the steel sheet according to the present invention may optionally contain (a) at least one species of Mo (no more than 1 mass%, excluding 0 mass%), Ni (no more than 0.5 mass%, excluding 0 mass%), and Cu (no more than 0.5 mass%, excluding 0 mass%), and (b) Ca (no more than 0.003 mass%, excluding 0 mass%) and/or rare earth element (no more than 0.003 mass%, excluding 0 mass%).

The present invention constructed as mentioned above provides a high-strength steel sheet which exhibits excellent bendability even though its strength as high as 600 to 1400 MPa. This steel sheet is suitable for automobiles.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 is a TEM photograph of the steel sheet (sample No. 4) according to the present invention.

Fig. 2 is a TEM photograph of the steel sheet (sample No. 13) according to the present invention.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

In order to develop a new steel sheet with excellent bendability, the present inventors carried out a series of researches. As the result, it was found that conventional DP steel sheets and TRIP steel sheets are poor in bendability because there is a large difference in strength between the parent phase and the second phase and this causes deformation to occur mainly in the interface between the two phases (that part of the interface which is adjacent to the parent phase).

The present inventors' further investigation revealed that the ultimate deformability (tight bendability) of TRIP steel sheets is affected not only by difference in strength between the parent phase and the second phase but also by the presence of carbide which does not undergo plastic deformation (or which is harder than the second phase). It was finally found that if the amount of carbide existing between retained austenite and ferrite is minimized, resulting TRIP steel sheets exhibit excellent bendability. The present invention is based on this finding.

Since the size of the carbide grain between retained

austenite and ferrite is approximately constant in the steel sheet according to the present invention, the condition of quantity of carbide is defined in terms of number of the carbide grains.

As mentioned above, the steel sheet according to the present invention is characterized by the minimal content of carbide existing between retained austenite and ferrite, which is specified by the number of carbide grains no more than 40 per 2000 μm^2. With the number of carbide grains exceeding 40, the resulting steel sheet is poor in bendability (especially tight bendability). The number of carbide grains should preferably be no more than 30.

The steel sheet according to the present invention should also have an adequately controlled structure so that it meets requirements for high strength as well as good elongation. The structure should be composed mainly of retained austenite (5-30 area%) and ferrite (no less than 50 area%). This limitation is based on the following.

Retained austenite (5-30 area%):

Retained austenite should be present in an amount of 5 area% (preferably no less than 8 area%) so that it helps increase total elongation. With an amount in excess of 30 area%, retained austenite adversely affects bendability. Therefore, the upper limit should be 30 area%, preferably no more than 20 area%.

Ferrite (no less than 50 area%):

The steel sheet according to the present invention should contain ferrite in an amount no less than 50 area%

so that it exhibits good ductility.

The steel sheet according to the present invention contains retained austenite and ferrite which constitute the main structure (accounting for no less than 70 area%). It may additionally contain bainite and martensite, which constitute the secondary structure, in an amount not harmful to the function of the present invention. These minor components inevitably remain in the structure during steel production. The amount of martensite should preferably be as small as possible.

Conventional TRIP steel sheets undergo heat treatment (after hot rolling and cold rolling) in the following manner. The work is heated and kept at a temperature higher than A_1 point and lower than A_3 point for about 60-180 seconds. Then, the work is cooled to a temperature in the zone for bainite transformation (for example, about 400±50°C) at an average cooling rate in excess of 10°C/s. The work is kept at this temperature for about 300 seconds so as to stabilize the gamma phase with an increased C concentration therein and to ensure a prescribed amount of retained austenite. Heat treatment in this manner, however, causes the C concentration to vary greatly from the inside to the outside of the retained gamma phase. This in turn gives rise to carbide, thereby deteriorating bendability.

According to the present invention, the steel sheet containing carbide in controlled form may be obtained by the manufacturing method which includes a step of keeping the work at a temperature in the zone for ferrite transfor-

mation (for example, about 700±30°C) for a prescribed period of time in the course of cooling from the retention temperature not less than A_1 point and not more than A_3 point to the temperature range of bainite transformation. In other words, this method requires that heat treatment be carried out in two stages so as to reduce difference in C concentration in the inside and outside of the retained gamma phase and to suppress formation of carbide between retained austenite and ferrite. It is to be noted, however, that the temperature zone for ferrite transformation overlaps with the temperature zone for pearlite transformation and hence keeping the work at that temperature for an excessively long period of time permits the pearlite structure to separate out, thereby deteriorating the characteristic properties. Therefore, it is necessary to keep the work at a heating temperature for an adequate length of time, which is about 10-30 seconds. In addition, it is not necessary for the work to be held in the temperature zone for ferrite transformation for a long period of time because C concentration in the gamma phase takes place rapidly. Therefore, this heat treatment may be carried out as part of the annealing step that follows hot rolling.

Incidentally, the conditions of the hot rolling and cold rolling that precede the heat treatment are not specifically limited. They may be properly selected among ordinary conditions. Also, the cooling rates after the heat treatments may be controlled adequately. For example, the average cooling rate in the case where the work is kept at

a temperature in the zone for ferrite transformation for a prescribed period time and then cooled to a temperature in the zone for bainite transformation is preferably larger than 10°C/s so as to prevent the formation of carbide.

The retained austenite steel sheet according to the present invention should have the specific structure and the controlled number of carbide grains as mentioned above so that it exhibits the desired properties. The steel sheet is not specifically restricted in chemical composition. However, it is desirable to control the amount of fundamental components (such as C, Si, Al, Mn, P, and S) as follows.

C : no less than 0.06 mass% and less than 0.25 mass%

C is an essential element for high strength and for ensuring retained austenite. C is an important element for obtaining an adequate amount of C in the austenite phase and for making a desired amount of the austenite phase remain at room temperature. The content of C to produce these effects should be no less than 0.06 mass%. C in an amount of 0.25 mass% or more adversely affects weldability.

Si+Al : from 0.5 mass% to 3 mass%

Si and Al effectively prevent the retained austenite from decomposing to form carbide. Si is also useful for solid solution strengthening. The total amount of Si and Al necessary for these effects is no less than 0.5 mass%, preferably no less than 0.7 mass%, more preferably no less than 1 mass%. Total amount of the elements exceeding 3 mass% makes the effects saturated. Excess Si and Al are

wasted without any additional effect, and they will cause hot shortness. Thus, the upper limit is 3 mass%, preferably 2.5 mass%, more preferably 2 mass%.

Mn : from 0.5 mass% to 3 mass%

Mn stabilizes austenite to give retained austenite as desired. The amount of Mn necessary for this effect is no less than 0.5 mass%, preferably no less than 0.7 mass%, more preferably no less than 1 mass%. Excess Mn produces an adverse effect, such as cracking in cast ingots. Therefore, the upper limit of Mn is 3 mass%, preferably 2.5 mass%, more preferably 2 mass%.

P : no more than 0.15 mass% (excluding 0 mass%)

P ensures as much retained austenite as desired. The amount of P necessary for this effect is no less than 0.03 mass%, preferably no less than 0.05 mass%. Excess P produces adverse effects in secondary operation. Therefore, the upper limit of P is 0.15 mass%, preferably 0.1 mass%.

S : no more than 0.02 mass% (excluding 0 mass%)

S deteriorates workability because it forms sulfide inclusions, such as MnS, to bring about cracking. The amount of S should be as small as possible. The amount of S should be below 0.02 mass%, preferably below 0.015 mass%.

The steel sheet of the present invention may optionally contain at least one of Mo, Ni, Cu, Ca, and rare earth elements in addition to the above-mentioned fundamental components. They improve the properties of the steel sheet when they are used in an adequate amount as specified in the following.

At least one of the following three elements.

Mo : no more than 1 mass% (excluding 0 mass%)

Ni : no more than 0.5 mass% (excluding 0 mass%)

Cu : no more than 0.5 mass% (excluding 0 mass%)

These elements strengthen the steel sheet, stabilize retained austenite, and secure a prescribed amount of retained austenite. Their respective amount necessary and sufficient for these effects is as follows:

Mo : no less than 0.05 mass% (preferably no less than 0.1 mass%), no more than 0.8 mass%.

Ni : no less than 0.05 mass% (preferably no less than 0.1 mass%), no more than 0.4 mass%.

Cu : no less than 0.05 mass% (preferably no less than 0.1 mass%), no more than 0.4 mass%.

Cr : no less than 0.05 mass% (preferably no less than 0.1 mass%), no more than 0.8 mass%.

The amounts of the elements exceeding the upper limits are wasted because of saturation of the effects.

Ca : no more than 0.003 mass% (excluding 0 mass%) and/or Rare earth elements : no more than 0.003 mass% (excluding 0 mass%)

Ca and rare earth elements control the form of sulfide in the steel, thereby contributing to workability. The rare earth elements used in the present invention include scandium (Sc) and yttrium (Y), both belonging to Group III, and lanthanide elements (atomic number 51 to 71). Any of them may be used in an amount no less than 0.0003 mass%, preferably no less than 0.0005 mass%. The upper limit is

0.003 mass%, preferably 0.0025 mass%. Any excess amount is wasted without additional effect.

The steel sheet of the present invention is composed of the above-mentioned components, with the remainder being iron. However, it may also contain Ti, Nb, V, etc. in small amounts, and the steel sheet containing such minor components is also covered by the present invention. In addition, the steel sheet of the present invention may contain inevitable impurities, such as Zr and B; they are permissible so long as their amount is small enough (less than 0.001 mass%) to save the effect of the present invention.

The invention will be described in more detail with reference to the following examples, which are not intended to restrict the scope thereof and which may be modified without departing from the scope thereof.

Examples

[Example 1]

A sample steel with the chemical composition shown in Table 1 was prepared by vacuum melting. The steel was made into a slab, which was subsequently made into a steel sheet (1.2 mm thick) by hot rolling and continuous annealing. Hot rolling was started at 1300°C and completed at about 900°C (which is higher than the Ar_3 point). The rolled sheet was wound up at a finishing temperature of about 450°C. The thus obtained hot-rolled steel sheet (2-3 mm thick) underwent cold rolling. The cold-rolled steel sheet (1.2 mm thick) underwent heat treatment (continuous anneal-

ing) in different patterns as specified below.

Pattern of heat treatment for samples Nos. 1 to 10.

This heat treatment consists of heating up to 850°C (above A_1 point and below A_3 point) and keeping this temperature for 120 seconds (for annealing), cooling to 700°C at an average rate of 5°C/s and keeping this temperature for 15 seconds, cooling to 420°C at an average rate of 15°C/s and keeping this temperature for 15 seconds (for austempering), and air cooling to room temperature at an average rate of 5°C/s.

Pattern of heat treatment for sample No. 11.

This heat treatment consists of heating up to 850°C (above A_1 point and below A_3 point) and keeping this temperature for 120 seconds (for annealing), cooling to 700°C at an average rate of 5°C/s and keeping this temperature for 60 seconds, cooling to 420°C at an average rate of 15°C/s and keeping this temperature for 15 seconds (for austempering), and air cooling to room temperature at an average rate of 5°C/s.

Pattern of heat treatment for sample No. 12.

This heat treatment consists of heating up to 850°C (above A_1 point and below A_3 point) and keeping this temperature for 120 seconds (for annealing), cooling to 420°C at an average rate of 15°C/s and keeping this temperature for 15 seconds (for austempering), and air cooling to room temperature at an average rate of 5°C/s.

Pattern of heat treatment for sample No. 13.

This heat treatment consists of heating up to 850°C

(above A_1 point and below A_3 point) and keeping this temperature for 120 seconds (for annealing), cooling to 420°C at an average rate of 15°C/s and keeping this temperature for 200 seconds (for austempering), and air cooling to room temperature at an average rate of 5°C/s.

Table 1

Steel Sample	Chemical composition (mass%)						
	C	Si	Mn	P	S	Al	Others
A	0.033	1.48	1.50	0.03	0.006	0.032	-
B	0.096	1.54	1.54	0.03	0.004	0.034	-
C	0.157	1.57	1.53	0.02	0.004	0.033	-
D	0.204	1.55	1.45	0.04	0.005	0.035	-
E	0.151	0.48	1.55	0.04	0.005	1.030	-
F	0.147	0.30	0.32	0.04	0.004	0.030	-
G	0.150	1.46	1.55	0.03	0.005	0.033	Mo:0.2
H	0.147	1.52	1.48	0.04	0.005	0.032	Ni:0.2
I	0.154	1.44	1.50	0.03	0.006	0.028	Cu:0.2
J	0.151	1.53	1.54	0.03	0.004	0.032	Ca:0.001

The thus obtained steel sheet samples were examined for the number of carbide grains per 2000 μm^2, tensile strength (TS), elongation [total elongation (El)], areal ratio (space factor) of each structure, and bending properties (tight bendability R_0 and bendability R_1) in the following manner. The results are shown in Table 2.

[Number of carbide grains]

Each sample undergoes electrolytic polishing (60 V - 0.5 A) with a solution containing 5% perchloric acid and acetic acid and etching (2 V - 20 mA, 2 min) with a solution of 10% acetylacetone and 90% methanol, containing 1 g of tetramethylammonium chloride. A replica of the sample is formed by carbon deposition and ensuing peeling. The replica is observed under a transmission electron microscope (TEM) with a magnification of 7500. Three arbitrary areas (each measuring 40 × 17 μm) of the sample are photographed. The photographs are examined to count the number

of carbide grains (per 2000 μm^2 = approximate total three areas) found between retained austenite and ferrite.

[Tensile strength (TS) and elongation (El)]

Each sample undergoes tensile test with a specimen conforming to JIS No. 5 for measurement of tensile strength (TS) and elongation (El).

[Areal ratio of each structure]

The microstructure of each sample (with its surface etched by Repeller corrosion method) is observed and photographed by using an optical microscope and a transmission electron microscope (TEM). The photographs are used to measure the areal ratio of each constituent. The areal ratio of retained austenite is determined by X-ray microanalysis (according to ISIJ Int. vol. 33 (1933), No. 7, p. 776).

[Bending properties]

Specimens (40 mm wide, 100 mm long, and 1.2 mm thick) are cut out of each steel sheet. They are subjected to tight bending R_0 and bending R_1 with a 1 mm thick steel sheet inserted (both through 180°). Their bending properties are rated in terms of cracking that occurs in the specimen. (Symbols "x" and "O" denote respectively the absence and presence of cracking.)

Table 2

No.	Steel type	Retained austenite (area%)	Ferrite (area%)	Bainite (area%)	Pearlite (area%)	Martensite (area%)	Number of carbide grains per 2000 μm^2	TS (MPa)	El (%)	R_0	R_1
1	A	0	96	0	0	4	6	460	33	O	O
2	B	9	84	5	0	2	12	594	34	O	O
3	C	13	79	6	0	2	22	673	33	O	O
4	D	16	77	6	0	1	25	855	31	O	O
5	E	11	86	3	0	0	18	649	29	O	O
6	F	0	83	5	12	0	--	545	22	×	×
7	G	12	82	5	0	1	20	982	24	O	O
8	H	13	80	6	0	1	13	872	29	O	O
9	I	12	83	4	0	1	9	902	27	O	O
10	J	13	80	5	0	2	17	650	32	O	O
11	D	3	70	3	24	0	--	785	21	×	×
12	D	17	76	5	0	2	56	878	29	×	×
13	D	13	83	4	0	0	65	860	33	×	O

The foregoing results may be interpreted as follows. Samples Nos. 2-5 and 7-10 exhibit excellent bendability because they meet all of the requirements prescribed in the present invention. Sample No. 4 gave a TEM photograph (×7500) as shown in Fig. 1. This photograph indicates that there exist a less number of carbide grains in the between retained austenite and ferrite.

By contrast, samples Nos. 1, 6, 11, 12, and 13 are not satisfactory because they do not meet any of the requirements prescribed in the present invention. Sample No. 1 is poor in strength on account of low carbon content. Sample No. 6 is poor in strength, elongation, and bendability because of insufficient retained austenite and excess pearlite structure which result from the low content of Mn and the low content of (Si+Al) combined together.

Sample No. 11 is poor in elongation and bendability on account of excess pearlite structure and insufficient retained austenite, which results from keeping the work at 700°C for a long time during heat treatment. Sample No. 12 is poor in bendability on account of a large number of carbide grains, which results from not keeping the work at 700°C during heat treatment. Sample No. 13 is good in bendability owing to stable retained austenite with a high carbon content but is poor in tight bendability (R_0) owing to a large number of carbide grains, which results from not keeping the work at 700°C but keeping the work at 400°C for a long time during heat treatment. Incidentally, Sample No. 13 gave a TEM photograph (×7500) as shown in Fig. 2. This

photograph indicates that the conventional steel sheet has a large number of carbide grains between retained austenite and ferrite.